

EVOLUTION OF GAS IN ELLIPTICAL GALAXIES

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ABSTRACT

We review the origin and structure of hot (cooling flow) gas in elliptical galaxies. X-ray observations can be used to determine the stellar mass to light ratio, the mass profiles of dark matter halos, and the interstellar magnetic field. Interstellar gas cools over a large volume, forming stars with a bottom-heavy IMF. For consistency with the thin fundamental plane, young stars must be optically luminous. Circular X-ray isophotes in rotating elliptical galaxies indicate distributed radiative cooling or strong interstellar turbulence.

Subject headings: galaxies: elliptical and lenticular – galaxies: structure – galaxies: fundamental plane – galaxies: cooling flows – x-rays: galaxies

1. Origin of the Hot Gas

The ratio of gas to stellar mass within giant elliptical galaxies is comparable to that in spiral galaxies, but the gas is much hotter, $T \sim 10^7$ K. Inside the half light radius ($r_e \sim 10$ kpc) most of the hot interstellar gas is produced by mass loss from the evolving old stellar population. Gas beyond r_e is also supplied by an inflow of local intergalactic gas which shocks to the virial temperature $T_{vir} \sim 10^7$ K. This more weakly bound gas can be stripped by ram pressure in rich clusters or either increased or depleted by tidal exchanges among galaxies in groups. The dominant stellar population in elliptical galaxies is typically very old, and the dissipationless assembly of the stars into the $r^{1/4}$ configurations observed today probably also occurred in the distant past, $z \gtrsim 1$. X-ray emission from the interstellar gas, often referred to as a “cooling flow”, indicates that the gas is losing energy. Paradoxically, however, the gas does not cool as it loses energy since it is immediately heated by Pdv compression in the galactic gravitational potential as the gas flows subsonically inward. The modest interstellar iron abundance ($zFe \sim 0.5 - 1$ solar) in $r \lesssim r_e$, mostly due to Type Ia supernovae,

indicates that supernova heating is not very important. The radial temperature gradient in cooling flows is small, $T \sim T_{vir}$ throughout.

It is easy to estimate the total interior mass $M(r)$ in elliptical galaxies by entering the observed hot gas density and temperature profiles into the equation of hydrostatic equilibrium. For several well-observed elliptical galaxies in Virgo the indicated mass in the range $0.1r_e \lesssim r \lesssim r_e$ is equal to the stellar mass, i.e., the (dynamically determined) central stellar mass to light ratio is accurate and fairly constant with galactic radius until the dark halo dominates beyond r_e (Brighenti & Mathews 1997). In the inner regions, $r \lesssim 0.1r_e$, however, the total mass indicated from the X-rays is less than the known stellar mass. This peculiar result can be understood if the hot gas there is being supported by some additional pressure, not included in the hydrostatic equation. The most likely source of additional pressure support is magnetic with strength $B \sim 100 \mu\text{G}$. Such central fields can arise quite naturally from turbulent amplification of stellar seed fields (Mathews & Brighenti 1997). The presence of these large fields may be completely independent of past or present AGN nuclear activity.

Simple gas dynamical models for the origin and evolution of hot gas in ellipticals have been quite successful (Brighenti & Mathews 1999a,b). The models begin with a tophat cosmological perturbation that develops into a Navarro-Frenk-White (NFW) dark halo growing in mass from the inside out. The baryons flow toward this perturbation, shock to $\sim T_{vir}$ and begin to lose energy by X-ray emission. At some early time, around age ~ 1 Gyr, stars are assumed to form with a Salpeter IMF, immediately releasing Type II supernova energy and metal enrichment. This starburst drives a strong shock wave upstream into the converging cosmic gas. At a slightly later time, ~ 2 Gyrs, after enough baryons have entered the halo, the de Vaucouleurs profile for the old stars is formed, simulating the merger process. From that time forward we solve the detailed gas dynamical equations, including stellar mass loss and Type Ia supernovae consistent with the observed rate. When the cooling flow gas is evolved to the present time, with continued inflow of gas from the local intergalactic environment, we find very good agreement with the observed hot gas density, temperature and iron abundance profiles in $r \gtrsim 0.1r_e$. The entropy and gas mass fraction within the hot gas are accurately reproduced in this calculation.

2. Where Is the Cooled Gas and How Did it Cool?

One of the great cooling flow mysteries, both on galactic and galaxy cluster scales, is the uncertain fate of cooled gas. For massive elliptical galaxies we know that the cooling flow cannot proceed all the way to the very center before cooling, even if angular momentum is ignored, because the masses of gas that cool ($\sim 4 \times 10^{10} M_\odot$) far exceed the masses of the central black holes observed in elliptical galaxies. Furthermore, VLA and other radio observations have set upper limits on the mass of HI and H₂ gas that are ludicrously small in many massive elliptical galaxies, $M(HI) + M(H_2) < 10^7 M_\odot$, so this endstate is not an option. Optical studies show that the cooled gas cannot be photoionized, typically $M(HII) \sim 10^5 M_\odot$ which is much too small. However, the universal evidence for HII gas in cooling flows with intermediate temperatures, $T \sim 10^4$ K, is clear evidence that the hot gas is indeed cooling over an extended region.

Even if the cooled gas is difficult to observe directly, its mass must contribute in a measurable way. X-ray data indicates that mass of old stars is sufficient to account for all mass in $r \lesssim r_e$. The best solution of this problem is to assume that the hot interstellar gas cools and deposits its mass over a large galactic volume within r_e , converting its mass rapidly into young stars (Brighenti & Mathews 2000a). It seems plausible that this cooling mass “dropout” is concentrated toward the center of the flow where the interstellar gas density and the radiation emissivity are greatest. Since there is no optical evidence for massive young stars in most elliptical galaxies, many authors have supposed that only very low mass stars formed from the cooled gas. However, unless the dropout profile is carefully orchestrated, dark baryonic stellar matter would interfere with the constancy of the dynamic mass to light ratio in $0.1r_e \lesssim r \lesssim r_e$ discussed above. An additional young population of low mass, optically dark stars would also cause a large, measurable scatter perpendicular to the fundamental plane even if elliptical galaxies were otherwise structurally and dynamically homologous (Mathews & Brighenti 2000). The best means of avoiding these difficulties is to assume that the continuously forming dropout stellar population is optically luminous with a mass to light ratio that does not differ greatly from that of the old dominant stellar population. It is possible to imagine how this could happen. The interstellar pressure in bright elliptical galaxies is about 10^4 times larger than in the Milky Way disk. As a consequence, very small masses of cooled HI or H₂ gas, $M \sim 2 M_\odot$ (weakly heated and ionized by X-rays; Mathews & Brighenti 1999), become Jeans unstable and collapse. If ~ 7 percent of the stars in large ellipticals have continuously formed with a Salpeter slope extending only to $\sim 2 M_\odot$, their contribution to the stellar H β index could explain the apparent youthful age of the stellar spectrum observed in many massive elliptical galaxies.

Spatially extended star formation in elliptical galaxies is obviously a difficult problem since the gas is about 10^6 times hotter than temperatures in typical star forming regions in the Milky Way. It has generally been assumed that localized thermal instabilities play an important role in concentrating the gas until gravity dominates. Thermal instabilities traditionally develop from small low en-

entropy regions of enhanced radiative emission where the gas density is slightly larger and the temperature is less than surrounding hot gas at the same pressure. Remarkably, Loewenstein (1989) showed that low entropy inhomogeneities oscillate radially in a cooling flow atmosphere and on average cool no faster than the surrounding flow, provided the perturbed regions move without drag. However, in reality the strong drag interaction with the ambient gas completely damps the oscillations. It now seems likely that small enhancements in the local interstellar magnetic field, not the entropy, may initiate cooling toward star formation. Magnetically buoyant regions can float at nearly a fixed radius in the cooling flow until the internal gas cools by radiative losses. In these floating regions, where most of the pressure is magnetic, radiative cooling proceeds at nearly constant gas density until the gas recombines and cools to star-forming temperatures (Mathews & Brighenti 1999; 2000). This model for localized cooling far from the centers of cooling flows is consistent with the recent discovery of spatially extended, cooler X-ray absorbing gas (Sanders, Fabian & Allen 2000; Buote 2000a,b).

3. Are Cooling Flows Really Heating Flows?

The uncertain physics of inhomogeneous cooling regions and low mass star formation in elliptical galaxies has led some authors to suggest that the cooling flows are not cooling at all, but are being heated by the release of energy from an active nucleus. Ciotti & Ostriker (1997; 2000) have proposed a model in which interstellar gas in all elliptical galaxies is intermittently and explosively Compton heated to $T_c \sim 10^9$ K by intense bursts of radiation from a central active nucleus, powered by a small amount of interstellar gas that cools onto the central black hole. Although the Compton temperature of observed AGN and quasar continua is very much less, $T_c \lesssim 10^7$ K, it would be difficult to observe the much harder Ciotti-Ostriker radiation continuum from elliptical galaxies if the time scale for the radiation bursts is sufficiently short. Binney & Tabor (1995) propose a similar model in which the accretion of a small amount of centrally cooled gas by the central hole leads to the production of violent radio jets and an expanding relativistic plasma that shocks and heats the in-

ner cooling flow gas sufficiently to offset its energy losses by thermal radiation. Later, as the energy of the relativistic plasma decays, the cooling flow is briefly re-established, more gas cools onto the central hole and the AGN radio lobe heating process repeats again. By this means it is argued that radiative cooling can be balanced by central heating so no distributed mass dropout is required. However, recent *Chandra* observations of the hot (cooling flow) gas surrounding the radio lobes of Hydra A (McNamara et al. 2000) and Perseus A (Fabian et al. 2000) show no evidence that the radio sources are heating the gas. Instead, the radio lobes appear to be pushing the hot gas aside, gently and adiabatically.

4. Why are Cooling Flow X-ray Contours so Round?

While the stellar systems in most X-ray luminous elliptical galaxies are not rotationally flattened, they do in fact rotate at $v \sim 50 - 100$ km s⁻¹. Gas lost from the rotating stellar system is rapidly heated to the virial temperature and must initially share the mean local stellar angular momentum. If this gas conserves angular momentum as it moves slowly inward with the cooling flow, it would spin up to the circular velocity $v_{circ} \sim 400$ km s⁻¹, and settle onto a thin cold disk of size $r_d \gtrsim r_e$. Remarkably, the flattening of X-ray isophotes that would accompany such a flow has never been observed, instead the inner X-ray contours are almost perfectly round (Hanlan & Bregman 2000). There are at least three explanations for this peculiar result (Brighenti & Mathews 2000b). Perhaps the most natural explanation is that angular momentum is lost by mass dropout in the cooling process. Alternatively, strong interstellar turbulence could transfer angular momentum to the outer regions of the cooling flow, but the turbulent energy density required exceeds that of known sources. Finally, torques from strong central magnetic fields, discussed above, may be sufficient to transport angular momentum away from the inner cooling flows.

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